PROGRESS REPORT
April 1, 1966 - September 30, 1966
NASA Grant NsG 107-61

MEASUREMENT AND DISPLAY OF CONTROL INFORMATION
(Remote Manipulation and Manual Control)

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DSR 79991-6

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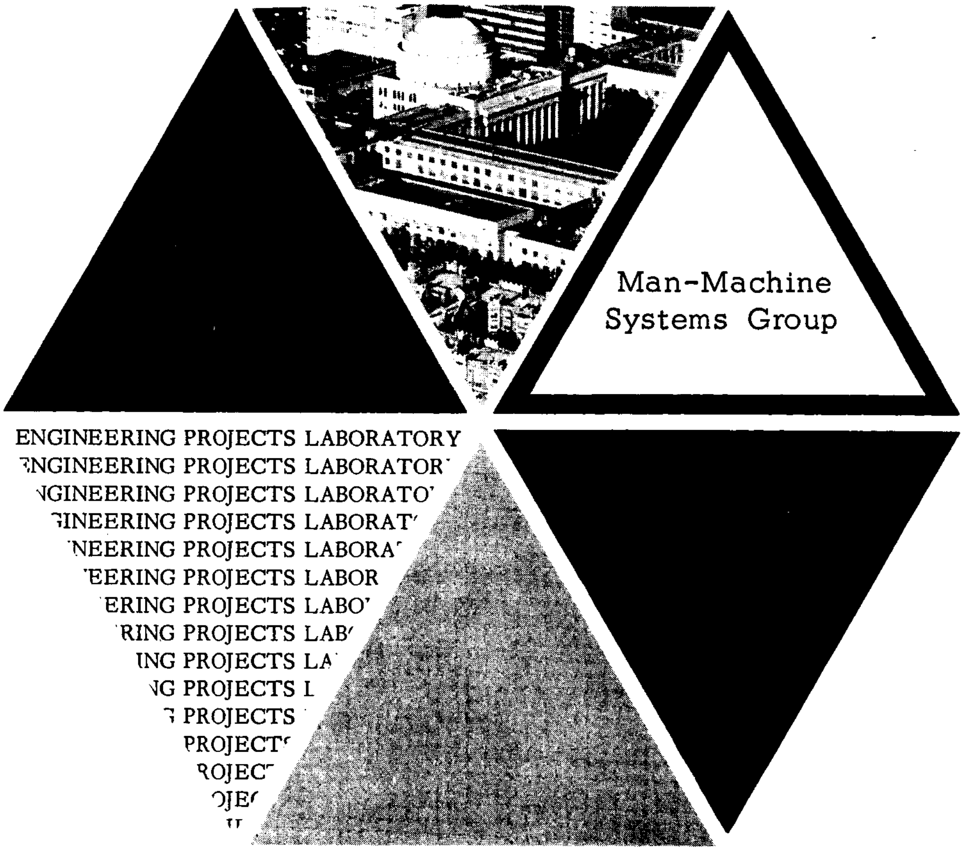

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This report is in two sections, the first dealing with remote manipulation, the second dealing with continuous manual control in the more conventional sense.

I. REMOTE MANIPULATION (personnel: D.J. Barber, W.L. Verplank, D.E. Whitney, J. Krafchick, W.R. Ferrell, T.B. Sheridan

A. Supervisory Control

Earlier work sponsored by this grant[1] showed if the telemetry transmission delay is long, experienced operators can achieve stable control and high accuracy by performing tasks in a sequence of open loop commands, separated by waits of one delay period for feedback. Such a strategy is economically feasible when transmission delay is short, when dynamic time constants inherent to the task are long, or when plenty of time is available for accomplishing the task. If these conditions do not obtain, it appears that the remote manipulator should be provided with artificial touch sensors and control logic such that continuous control within telemetry subtasks can be carried out autonomously and without transmission delay through a control loop at the remote site. This relegates the human operator to the role of a supervisor, controlling over a long-distance delay loop: he intermittently evaluates the remote manipulator's performance and commands new subgoals or subroutines for the remote manipulator to execute (Fig. 1). A local loop is also pictured in Fig. 1, representing the human's use of computer and controls to study and experiment with the implications of various commands before making them. Our efforts have concentrated on this general problem during the last year.

A study by S.G. McCandlish[2] used an all-digital simulation and display (Fig. 2) of a remote manipulator in a very simple task of removing

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[1]Ferrell, W.R., Remote Manipulation with Transmission Delay, NASA TN-D 2665, Washington, D.C., Feb. 1965.

[2]McCandlish, S.G., A Computer Simulation Experiment of Supervisory Control of Remote Manipulation, Engineering Projects Lab. Report No. DSR 9960-2, M.I.T., Cambridge, Mass, June 1966.

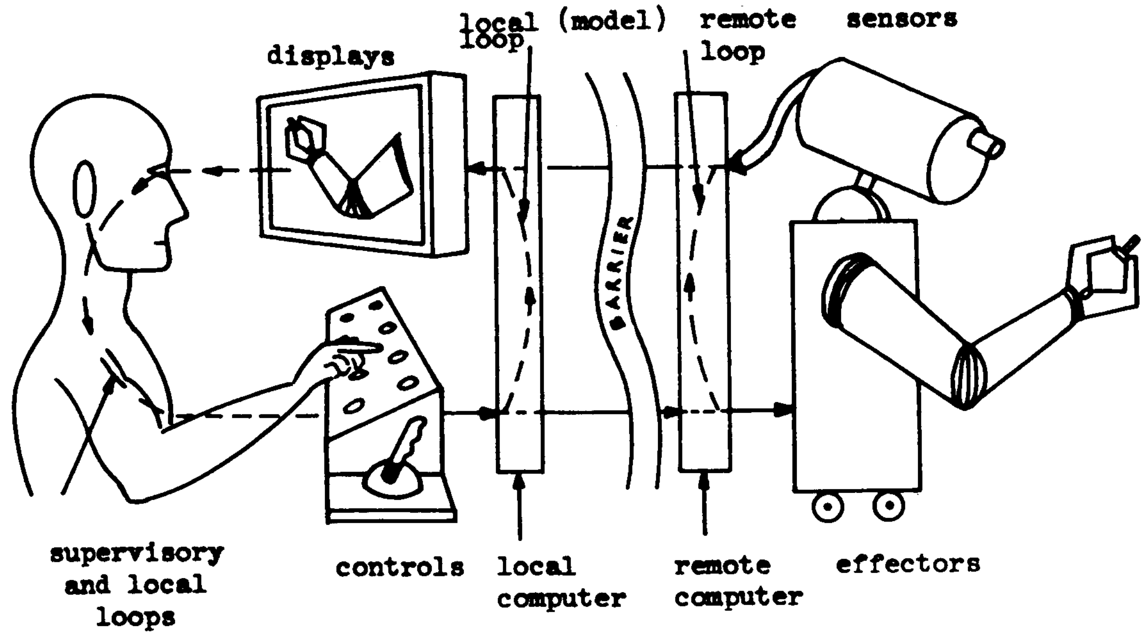

Figure 1. Schematic diagram of supervisor-controlled remote manipulation system.

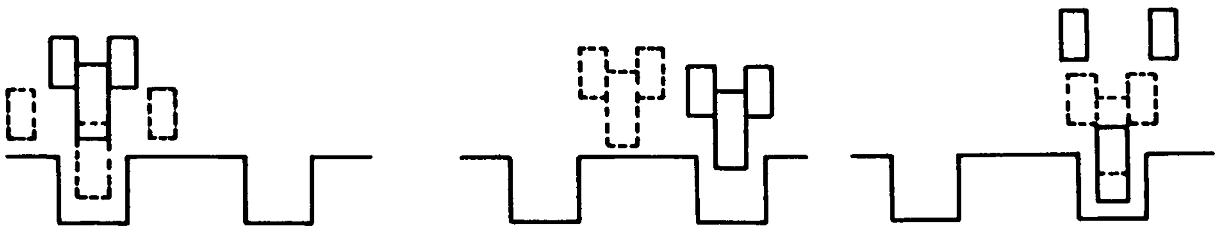

Figure 2. Computer-generated display of simple manipulation task used in McCandlish experiment. In each of the three views of the jaws, manipulated object, and two-hole environment, the dotted lines represent the start and the solid lines the termination of an available subroutine.

a block from one hole and inserting it in another hole. Control was either by direct on-off rate control in each degree of freedom or by calling subroutines. The direct control mode was more easily learned, but for long delays the supervisory (subroutine) control mode took less time and required fewer open loop moves. Parallel with McCandlish's study was an effort by T. Rarich[3] to adapt a 7 degree-of-freedom mechanical hand, previously equipped with servomotors by H. Ernst, to the supervisory control mode. Rarich developed several supervisory modes which the operator could command from the teletype console (Fig. 3). These commands are listed in Table 1. Rarich's modification included a touch sensor with spring loaded micro-switches on each jaw. (Fig. 4)

Closing the servo loop through the computer in the way that Rarich had done proved unsatisfactory in several respects, and without concluding that this approach could not be improved upon, it was decided to equip a second manipulator with stepping motors. These motors, which give a rotation increment for each pulse input, have sufficiently high torque that for most manipulation tasks they will not slip. This hardware has been interfaced with the PDP-8, and programs have now been written by Barber for the stepping motor manipulator to enable the operator to command all of the control modes of Table 1.

In addition to using the teletype as a controller, experiments have been conducted by Verplank with a portable 7 degree-of-freedom controller device which attaches to the operator's shoulder and articulates similarly to his arm (Fig. 5). Each degree-of-freedom has a three position toggle switch. This device permits more "natural" or anthropomorphic control than the teletype, even though manipulator position is the time integral of controller switch position. In using this device the operator may track the manipulator orientation with his own arm and body, thus keeping his own arm position in spatial correspondence with the manipulator arm position in each degree-of-freedom.

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[3] Rarich, T.D., Development of SCM-1 A System for Investigating the Performance of a Man-Computer Supervisory Controlled Manipulator, Engineering Projects Laboratory Report No. 9991-3, M.I.T., Cambridge, Mass., May 1966.

Figure 3. Human subject controlling mechanical hand to pick up coffee cup through use of symbolic commands.

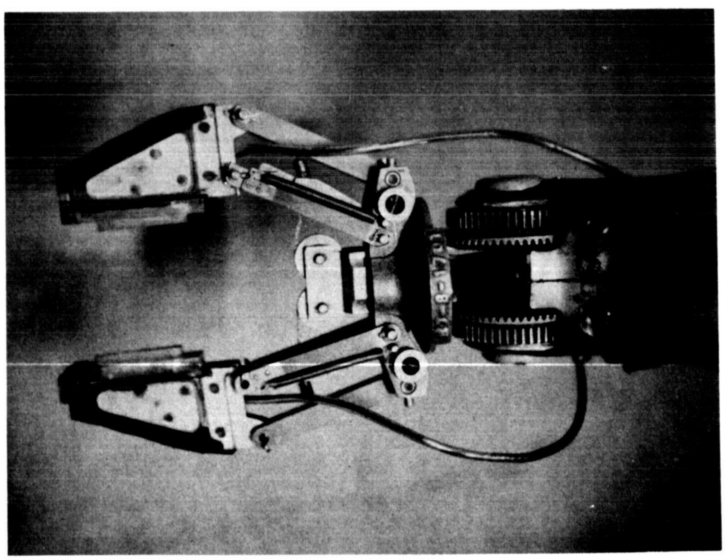

Figure 4. Detailed view of manipulator hand showing wrist articulation and touch sensors on distal and palmar surfaces of two jaws.

Table I

Command Modes

1. Rate Control   YL20 (motor Y, direction L, speed 20) plus stop, jaw open, jaw closed.

2. Increment Control YL20 (motor Y, direction L, distance 20) plus jaw open, jaw closed.

3. Configuration Name   User can name position configuration and at later time have manipulator resume that position merely by calling that name. Can also erase names.

4. Touch Sensor Satisfy   User can specify one of a combination of touch sensors and indicate ON or OFF. Computer will decide direction to move and will stop only when that combination of touch sensors is turned on or off.

5. Emergency Instructions, Calibration Instructions, etc.

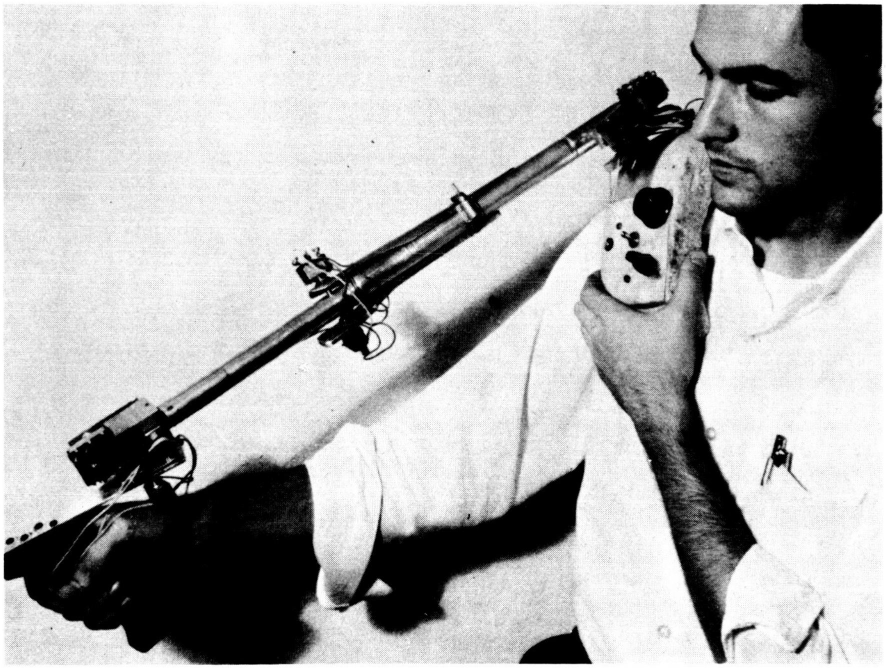

Figure 5. Analogic controller devices. In each of seven degrees of freedom (which correspond to manipulator) operator can operate a three positional (plus, zero, minus) switch. Knobs on the shoulder piece are for switching computer modes (increment, rate, etc.).

Current programming efforts by Barber are aimed at enlarging the flexibility of commands available to the human operator by: 1) permitting the human operator to reference commands relative to hand's present orientation; and 2) permitting a human to input branching conditional statements which the manipulator executes when its own sensors satisfy the given conditions. Regarding (1) above, there are no feedback potentiometers on the stepping motor manipulator, so that bookkeeping of the current state of each degree of freedom is done by a count register. From this it can easily be determined which degrees of freedom to activate to move the hand in a particular direction or to a given orientation relative to its present position or orientation. Given the initial and terminal positions, there remains the question of what alternative combinations of movements are best. "Best" may be determined by such factors as shortest path, least number of degrees of freedom actuated, positions of obstacles which must be avoided in reaching the subgoal, etc.

Conditional statements [(2) above] are such commands as:
DISPLACE HAND LEFT UNTIL 40 OR TOUCH 2 OR 3.
IF 40 STOP, OTHERWISE ROTATE HAND RIGHT UNTIL 90 OR TOUCH ANY.
IF 90 STOP, OTHERWISE 527.
While such statements appear no different from any other computer language instruction to a digital computer, the important new feature in the present context is that the human operator is using symbolic statements extemporaneously to control a multi-degree-of-freedom dynamic system continuously and in real time. Words, of course, may be replaced by other symbols providing they have meaning to both human commander and machine interpreter. The concatenation also is arbitrary, but should be of some form "natural" for human use. Move commands are "displace" and "rotate". "Hand left" means move whatever degrees-of-freedom are necessary that the hand go toward <u>its</u> left (left in its own reference system). Termination of this command depends upon either completion of 40 units of translation or the actuation of either touch sensors 2 or 3.

If 2 and 3 were not on the hands' own left the manipulator could refuse to execute until clarification were provided by the human. The period indicates an expectation that branching will be satisfied. If conditions for branching are not satisfied the manipulator can stop and ask for help. In the next statement "touch any" means the condition of any touch sensor active. 527 in the last statement is a call to a subroutine.

Under consideration are several command subroutines which would seem to be useful in manipulation. One is a routine which makes a series of pokes along a flat surface until a discontinuity is detected, Fig. 6a. A second is a routine which moves both jaws of the manipulator in the close grasp direction, and stops each jaw as it touches, Fig. 6b. The grasp degree-of-freedom closes both jaws symmetrically with respect to the manipulator wrist; thus a special subroutine must be provided such that after the first jaw makes contact, in order to keep that jaw stationary the wrist tanslates and moves the contacting jaw away at the same rate the closing grasp moves the contacting jaw into the object.

B. Formal Description and Theory

The study of human hand function has not been graced by theory. In any mechanical manipulation task the use of mechanical hands forces applied to manipulated objects are related to control handle displacements (or symbolic commands) in rather complex ways. Thus conventional control theory, which has been applied successfully to manual tracking, does not readily apply to the highly nonlinear state space of manipulation.

The theory of undirected graphs is being explored by D. Whitney for use in modelling manipulation tasks, with the state space (positions and orientations of manipulator and manipulated objects) represented by nodes on the graph. Only some nodes are connected (transitions are possible) because of obstacles or mechanical constraints, and only some connections

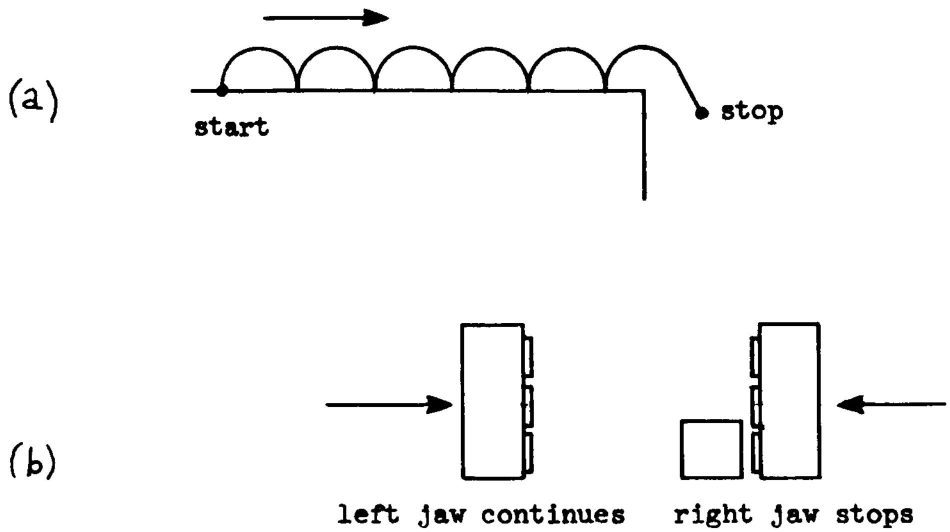

Figure 6. Command subroutines: a) test surface in given direction for corner; b) grasp object without displacing it.

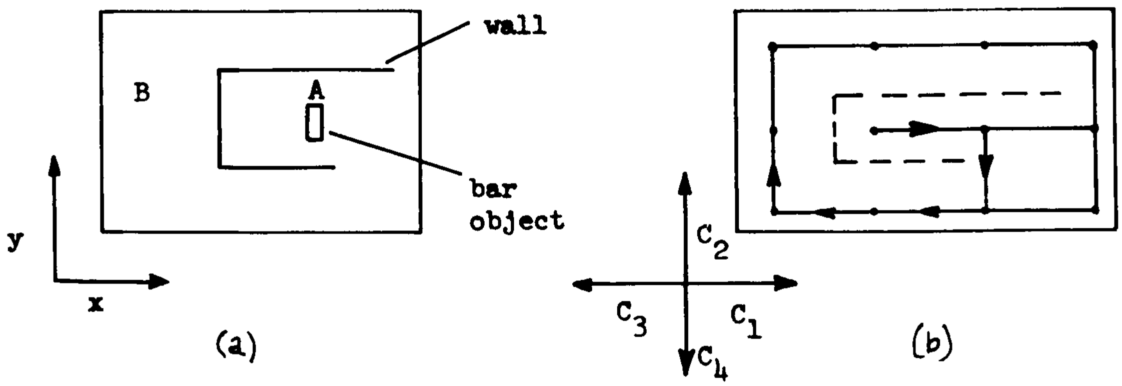

Figure 7. Simple test for manipulator graph search algorithm.

are reversible, e.g. a grasped object drops if released in a gravity field, but may not be "undropped". Presumably, certain costs (in terms of energy, time, etc.) are incurred by certain connections. There are two separate problems: one is the definition and specification of the nodal space with suitable connections and costs. The second is how, given a specified state space, can a man and computer work together to complete a task for reasonable (not necessarily minimum) cost.

Because of the large number of dimensions inherent in most manipulation tasks optimization algoithms such as dynamic programming obviously are not practicable for the whole task. But, if the human provides a judgment as to one or alternative subgoals which are near the present state, local regions of state space may be explored by a fast-time computation and best local paths chosen. Thus the human may be relieved of the task of specifying in detail how a given command is to be carried out.

As an example assume that the bar in Figure 7a lies on a small table. We want to slide it (no lifting allowed) from location A to location B. The hook-shaped wall is in the way. We tell the computer that the goal is B and allow the computer to use a string of commands chosen with replacement from the set.

C_1	=	move	one	inch	parallel	to	x	axis,	plus	direction
C_2	=	"	"	"	"	"	y	"	"	"
C_3	=	"	"	"	"	"	x	",	minus	"
C_4	=	"	"	"	"	"	y	",	"	"

Figure 7b is a simple graph of this situation (notto scale). The dots correspond to locations on the table which are one inch apart. The lines show which commands are allowed at each location. The shortest path (cost = distance) is shown with arrows, and corresponds to the sequence of commands C_1--C_4--C_3--C_3--C_2. The computer can deduce the graph by exploring, can obtain the path given A and B using a shortest path algorithm, and can carry out the sequence thus obtained using methods explored by Ernst and Barber, which will be further explored.

Effort is being directed toward finding ways of coding the multidimensional information specifying a manipulation task into several graphs of two or perhaps three dimensions. This will save vast amounts of data storage space and will make the method practical but may cause some inefficiencies in carrying out the tasks.

The minimal manipulator (with three degrees of freedom, all on a plane: x,y grasp) has been converted from servomotors to stepping motors by Whitney. Programs have been written to enable it to control through the PDP-8 which in turn is commanded by a human using a typewriter.

C. Touch Sensors

At the outset of this project it became evident that long-distance remote manipulation would require that the human operator (and/or a computer controller) be able to sense the patterns of contact pressure between manipulator hand "skin" and manipulated objects. This is distinct from visual sensors and displays, already highly developed in the form of closed circuit television, but possibly not useful for tasks where light transmission between manipulated objects and sensors is obscured by intervening opaque particles or objects. It is also distinct from what is often called "force-reflection", indication of the gross force resultant imposed upon the remote manipulator in each degree of freedom and measured by strain-gages and the rigid segments of the manipulator mechanism or by current or pressure readings from the electrical or hydraulic motor driving each degree of freedom. By analogy to human senses, the contact pressure or touch pattern sense is to the human skin senses as force reflection is to the muscle and tendon senses; it measures position and motion of manipulated objects relative to the skin surface.

Several such touch sensor devices have been developed[4,5] and described in previous progress reports.

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[4]Kappl, J.J., A Sense of Touch for a Mechanical Hand, S.M. Thesis, Department of Mech. Engr., M.I.T., Cambridge, Mass., August 1963.

[5]Strickler, T.G., Design of an Optical Touch Sensing System for a Remote Manipulator, S.M. Thesis, Dept. of Mech. Engr.. M.I.T., Camb., Mass., June 1966.

Recently Whitney has outfitted each jaw of the minimal (planar) manipulator with three touch sensors based upon carbon material suspended in rubber commercially available from Coe-Myer Co. in Chicago. Great care was required in fabricating these devices in order to make them reliable. For the supervisory control experiments described above, the only touch sensor to be used is that shown in Fig. 4, giving only binary contact information at each of a small number of areas on the slave hand. However most of the touch sensor developments to date including Strickler's deforming mirror device have been designed to provide the human operator with a contact pressure display which is spatially continuous and not necessarily intended to be used in a supervisory control mode. Evaluation of these devices has not been extensive because we believed the most critical tests of their effectiveness would be in direct manual (non-supervisory) master-slave remote manipulation tasks where vision and force reflection were severely limited. The manipulators we have been using in the laboratory simulation have not permitted direct master-slave control without the built-in force reflection caused by the mechanical tapes connecting master hand to slave which transmit forces between the operator's hand and the manipulated object.

Present efforts by Krafchick are to achieve a direct master-slave control mode without force feedback by driving the stepping motor manipulator, through the computer, from position potentiometers of the servomotor manipulator with the human operator controlling the master end of the latter (Fig. 8). Various touch sensor configurations will be attached to the slave of the stepping-motor manipulator and serve, in some instances, as the only feedback. In other cases purposely degraded television will be provided.

II. CONTINUOUS MANUAL CONTROL (personnel: D.C. Miller, P.A. Hardin, R.D. Roland, A. Miller, W.R. Ferrell, T.B. Sheridan)

A. Time-Optimal Control of a Second Order System by a Human Operator

A very general question of interest is to what degree the human is an

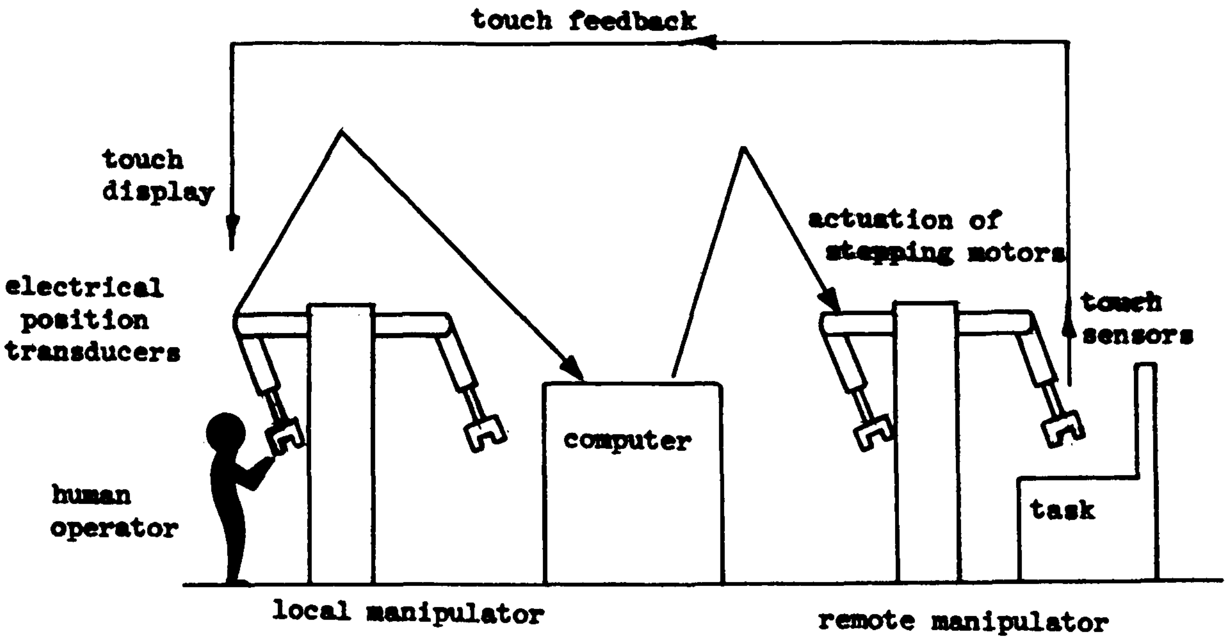

Figure 8. Use of two mechanical hot laboratory manipulators for touch sensor evaluation and use of "local model". Electrical sensors on left manipulator drive, through the computer, stepping motor on right manipulator. Touch patterns are relayed back to operator through closed circuit T.V. Operator can be isolated from force and/or visual feedback from remote manipulator but has full force and visual feedback from "local model" manipulator.

optimal controller for a given type of performance criterion and a given class of system[6]. In seeking an empirical answer to this question it is not enough simply to tell the human subject the criterion and provide him the system. His behavior will be dependent in large measure upon his experience with the same or different systems and the same or different criteria. It will also depend upon the human operator's display of both state variable and criterion cost.

D. Miller has begun an investigation of a human's ability to bring a second order linear system to rest (to within a tolerance on position and rate) in minimum time. This task was chosen as a starting point because it has a readily obtainable analytic solution and because a display of its state variable requires no more than two dimensions. Initial experiments have dealt with the system

$$\frac{d^2y}{dt^2} + \omega^2 y = K x \quad , \quad \omega = \frac{1}{2} \text{ rad/sec.}$$

The variable x is controlled by a three state (plus, zero, minus) hand controller. Four displays are being employed (Fig. 9): 1) position only; 2) position and rate (phase plane); 3) same as (2) but with a predictor trace (extrapolation of system response from present initial conditions); 4) same as (2) but with optimum switching curve indicated on the display. The latter display, when used by a subject who knows he is supposed to switch at the switching line, serves as an experimental control.

Results so far indicate that most experienced subjects settle down to a switching policy as shown in Fig. 10. These experiments are being continued with other linear as well as non-linear time-optimal control tasks. Eventually the criterion may be modified to time-optimal control with the constraint that certain "forbidden areas" of state space be avoided.

B. Dynamic Programming in Self-Paced Systems

P. Hardin, both in a recently completed thesis and in continuing efforts,

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[6] Sheridan, T.B., Fabis, B.F. and Roland, R.D., Preview Control Behavior and Optimal Control Norms, Proc. 1966 NASA/University Working Conference on Manual Control, Feb. 1966, in press.

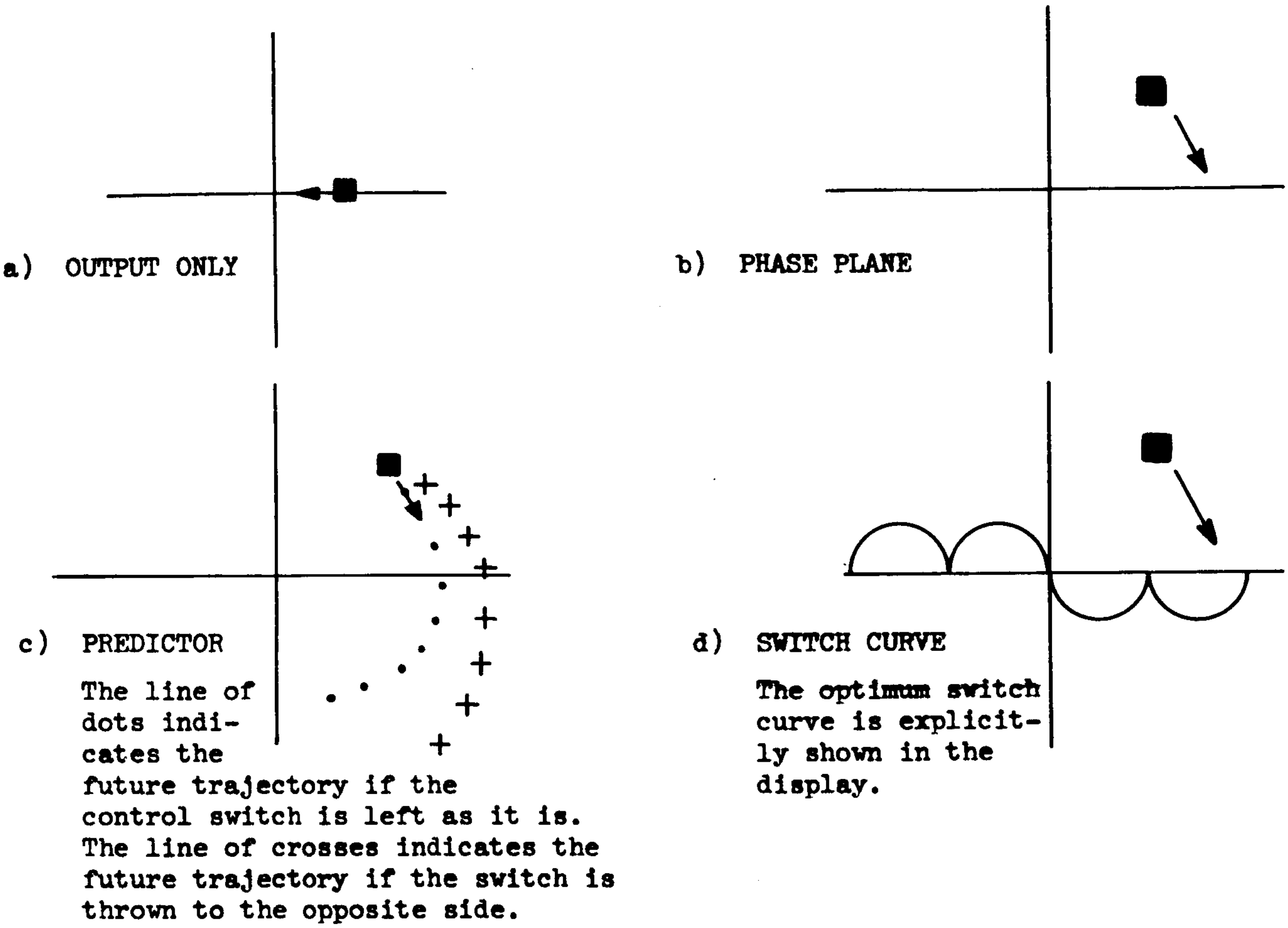

Figure 9. Four state displays of second order control task used by Miller.

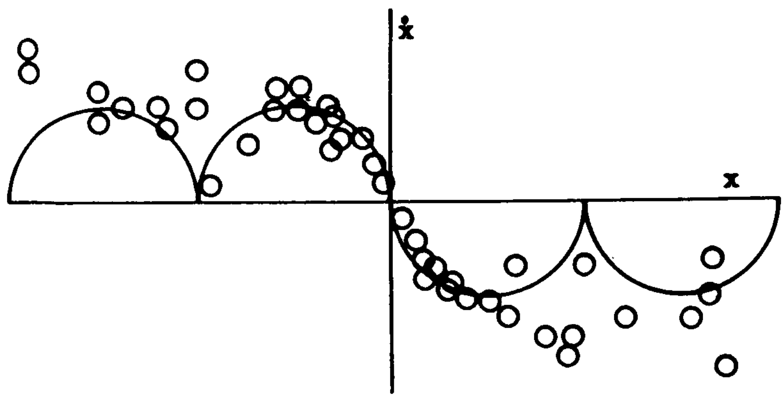

Figure 10. Preliminary results of Miller experiment. Human switch points compared with optimal switch points on phase plane.

has studied the applicability of computer optimization algorithms to second order systems of the so-called self-paced type, systems where the independent input is a course in space to be traversed, not a forcing function of time.[7] Solutions were formulated using three types of algorithm: 1) Bellman's dynamic programming[8] in almost its conventional form; 2) a modification of dynamic programming in which only trajectories near some nominal starting trajectory are considered, and on successive iterations of the algorithm the region of state space under consideration is progressively shrunk in total range and more finely reticulated; 3) classical gradient analysis.[9]

Most of the problems considered were of the type shown in Fig. 11, control in two dimensions, x and y, with a "forbidden region" to be avoided and a constraint that the system start at rest at the lower left and end at rest at the upper right. This task, we believe, or slightly more complex versions of it, is not unlike what people do in landing aircraft, driving cars through traffic etc., and will provide a kind of task with which we can later challenge human subjects. The performance functions were either

$$J = \sum_{t=0}^{N} \left\{ [\ddot{x}(t)]^k + [\ddot{y}(t)]^k + \text{position cost }(t) + \text{time cost }(t) \right\}$$

or

$$J = \sum_{t=0}^{N} \left\{ \left([\ddot{x}(t)]^2 + [\ddot{y}(t)]^2 \right)^{k/2} + b \left([\dot{x}(t)]^2 + [\dot{y}(t)]^2 \right)^{k/2} + \text{position cost }(t) + \text{time cost }(t) \right\}$$

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[7] Hardin, P.A., Simulation and Analysis of Self-paced Second Order Control Systems, M.S. Thesis, Dept. of Mech. Engr., M.I.T., Cambridge, Mass., August, 1966.

[8] Bellman, R.E. and Dreyfus, S.E., Applied Dynamic Programming, Princeton: Princeton University Press, 1962.

[9] Boehm, Barry, "Trajectory Optimization by the Gradient Method; A Report on the Bryson-Ho Short Course at Harvard", Rand Corp., Aug. 15, 1963.

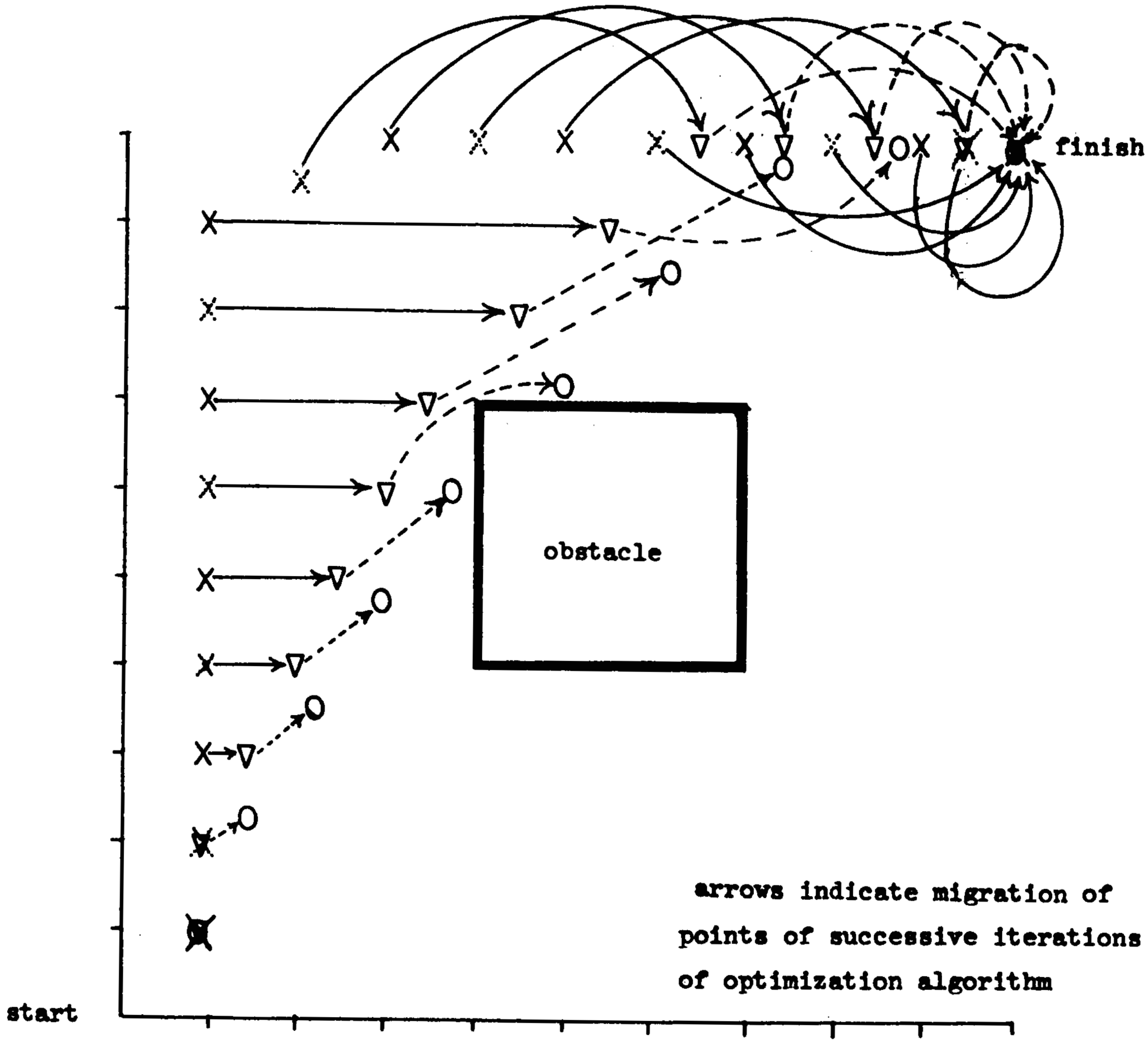

Figure 11. Two-dimensional physical space of Hardin's self-paced dynamic programming simulation. State space is five dimensional (position and velocity in each of two physical dimensions, plus time or number of steps). Problem may be considered that of controlling a second order system which starts at lower left and ends at upper right.

where position cost is incurred for stepping into the forbidden region and time cost is incurred for all t short of the terminal state. Note that when stated in this way in order to determine the optimal trajectory there is no need for the so-called system equation relating x and y to some control variable.

For conventional dynamic programming keeping all the states of a two dimensional second-order system plus the time argument in the available 24000 36 bit words of memory permitted only a very coarse grid: 10 x by 10 $\dot{x}$ by 10 y by 10 $\dot{y}$ by 10 time units with each number limited to seven bits. The reason for formulations (2) and (3) outlined above was to permit a finer grid and still maintain all the information in core.

The modification of Bellman's conventional algorithm mentioned above is that, rather than computing and storing different positions and velocities resulting from unit differences in the control variable (and in some cases having to approximate the resulting position), we let the system assume only those velocities and accelerations which can be stated in terms of an equal interval position space, and compute the resulting costs. Thus far this method has appeared simpler and more expedient.

From our experience to date we conclude tentatively that dynamic programming optimization over state space large enough to model continuous manual control is not practical; gradient optimization is not satisfactory in a space that has well bounded obstacles (infinite gradients in cost space or at best small regions of large finite gradients). Thus the most promising for the present class of problems seems to be the iterated dynamic programming algorithm which successively centers its attention in the region of the best trajectory so far and progressively "shrinks". This method is not immune from getting stalled in local minima or in producing a multiplicity of optimal trajectories (optimal for the discrete grid) as shown in Fig. 12. If the starting nominal trajectory was one with relatively few large steps the computation was especially prone to getting trapped in local minima.

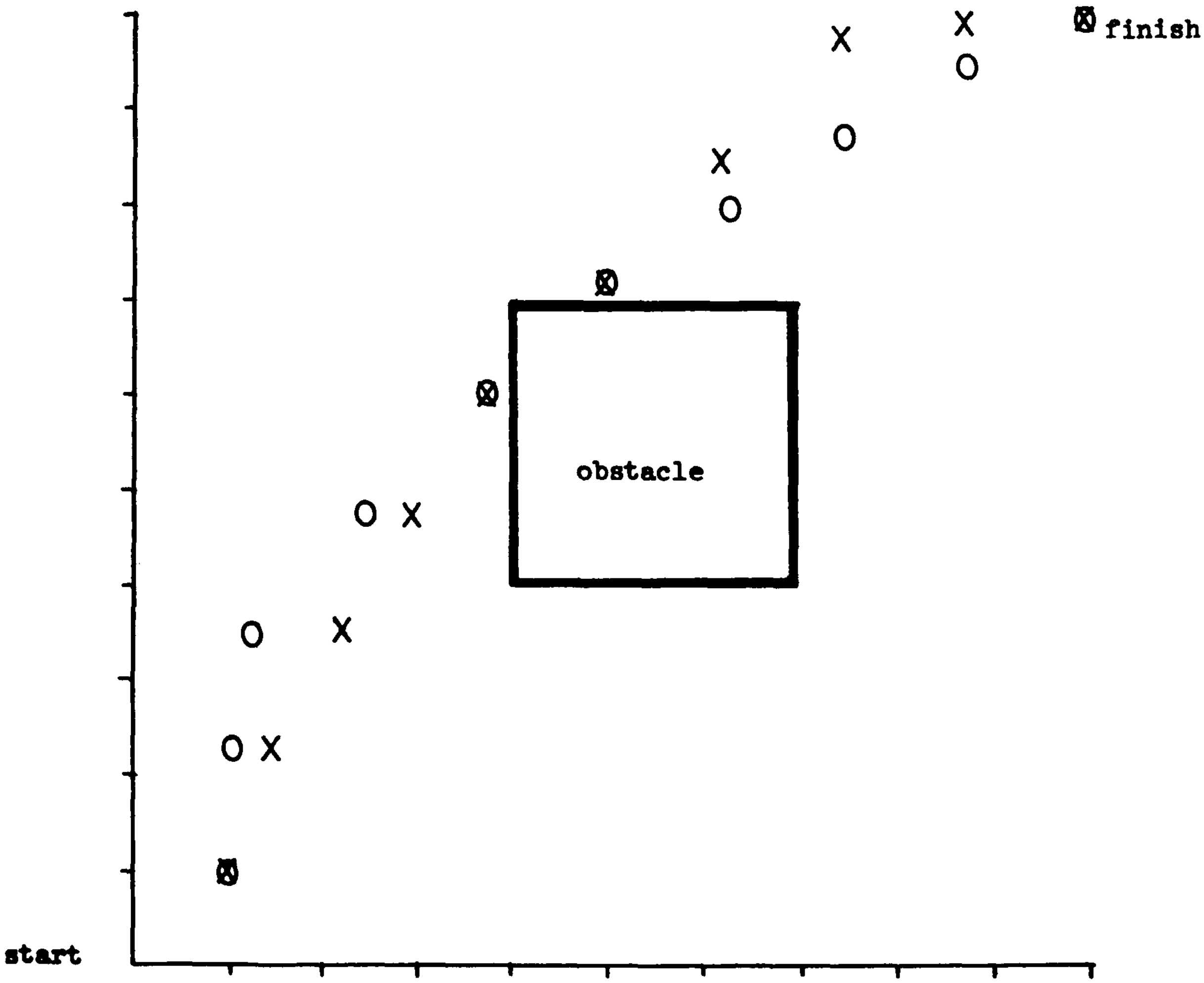

Figure 12. An example of two trajectories (x's and o's) which are optimal (in discrete space) for a given criterion. Both have cost 19.0 and time 4.5.

C. Preview Control Model

Continuing on from work on preview control described in previous progress reports and elsewhere[10], two projects have been initiated. One, by A. Miller, seeks to modify the two-time scale control experiments reported earlier, in particular that in which a proportional control system with a nominal gain K and a fast-time dynamic model of the actual real-time controlled process was made to track in fast-time that portion of the controlled input which was "seen ahead". To the degree to which the high speed model's response does not match the input (ideal response) over the preview span, the real-time control of the actual system is "augmented" over and above that normally resulting from the nominal proportional controller. The best form of augmentation is still not clear. The earlier experiments included the undesirable feature that the "nominal gain" of the fast-time controller was unity, and that trial errors of the model control system were far too large.

A second aspect of preview control is being investigated by H. Vickers, who is considering what can be done with simple linear filters whose weighting functions operate upon "future inputs" (future relative to the time where the response to such inputs begins). Some of his initial results suggest that a direct analogy is possible between two time-scale systems of the type described above and forward looking filters optimized through use of the Weiner-Hopf equation.

A third aspect of preview control is being studied by W.R. Ferrell. There is a maximum information transmission rate for continuing sensory-motor tasks such as typing, reading aloud, and tracking when the operator can see ahead and pace himself. The maximum rate varies with the operator and the task but tends to be constant as the redundancy of the material is varied. Reducing the operator's view ahead reduces the information transmission rate. For typing it was found that the variable that determines the maximum rate is the average information available in the preview and not the distance ahead. Initial evidence suggests this might

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[10] Sheridan, T.B., "Three Models of Preview Control", IEEE Transactions Human Factors in Electronics, Vol. No. HFE-7, No. 2, June 1966.

also be the case for self-paced tracking and experiments are underway to test this hypothesis.

D. Experiments with Human Subjects in Optimal Control of Previewed Inputs

Some experiments further to those previously performed under this grant were done by R.D. Roland, in a thesis[11] concerning driving simulation and supported in part by the U.S. Public Health Service. A dot, moving vertically on an oscilloscope display at constant velocity, has $1/s^2$ dynamics horizontally, such that each time a spring loaded telegraph key was tapped left or right the horizontal velocity was increased by one unit in that direction. The experimental set up was improved over the previous experiment in that the grid was 64^2 rather than 15^2 and the control key incorporated a Schmidt trigger, requiring a discrete tap for each acceleration.

On each run, two targets appeared at constant (different from each other) vertical position, but were randomly assigned to one of three horizontal positions. The task was to produce a trajectory which minimized score, obtained from the criterion

$$J = \sum_{i=1}^{2} \left\{ 2[X_{\text{target}} - X_{\substack{\text{controlled}\\\text{variable when}\\\text{at same } y}}] + \begin{matrix}\text{number of}\\\text{acceleration pulses}\end{matrix} \right\}$$

The subjects learned the meaning of this performance function through practice. Three subjects, after practice, did five runs on each target configuration at each of three speeds, 1.6, 3.2 and 4.8 cm per second, the speed and target position being assigned in pseudo-random order. Results for the two most difficult target configurations, the two dots which are shown in Fig. 13a or for its mirror image, are presented here. Fig. 13a shows average response trajectories for a less experienced subject, Fig. 13b for a more experienced subject. In the plots shown and the other data,

[11] R.D. Roland, Experimental Study of Preview Control in Simulated Driving Task, S.M. Thesis, Dept. of Mech. Engr., M.I.T., Cambridge, Mass. August 1966.

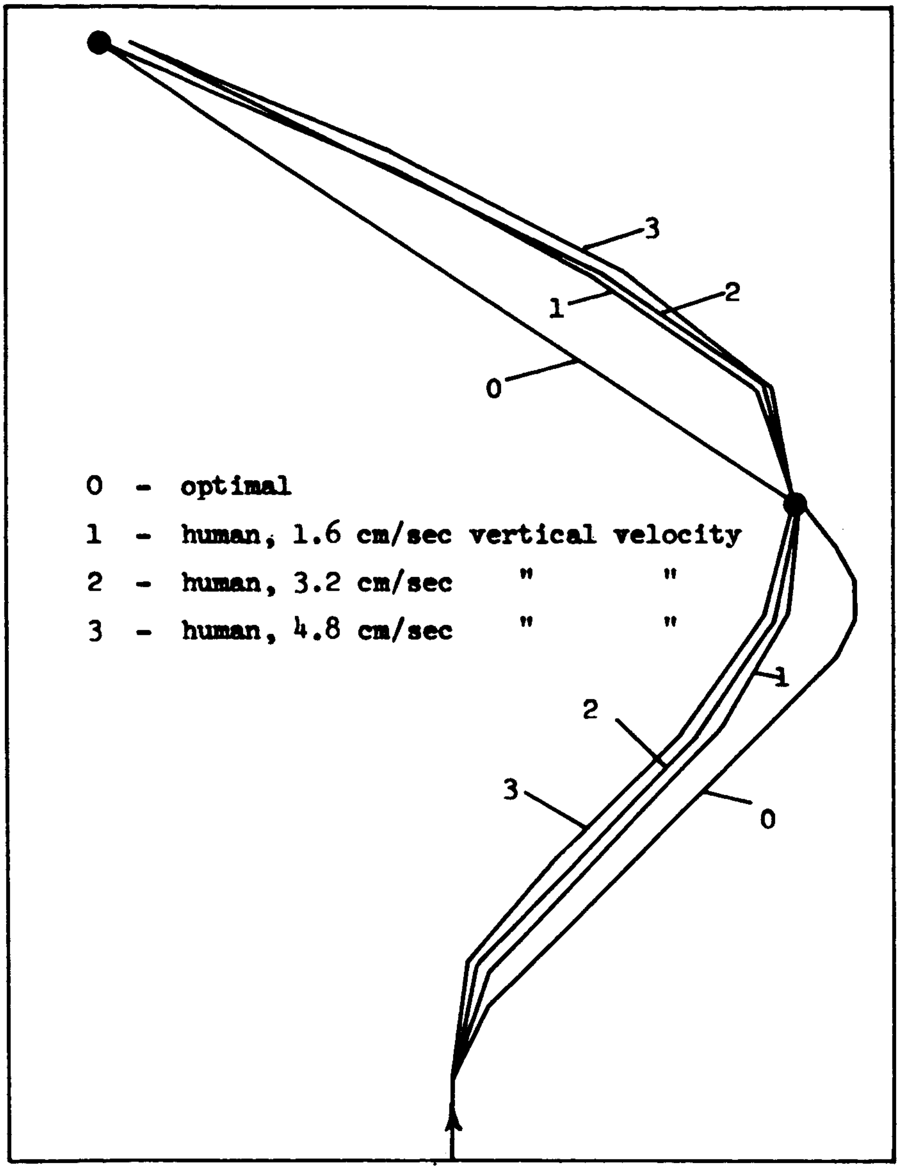

Figure 13a. Human attempt to produce optimal trajectory in two target experiment. Less experienced subject. Spot started at bottom and moved with constant velocity to top; each time subject tapped key left or right, velocity changed by one increment in corresponding direction. Trajectories shown are averages of fifteen runs at indicated vertical speed.

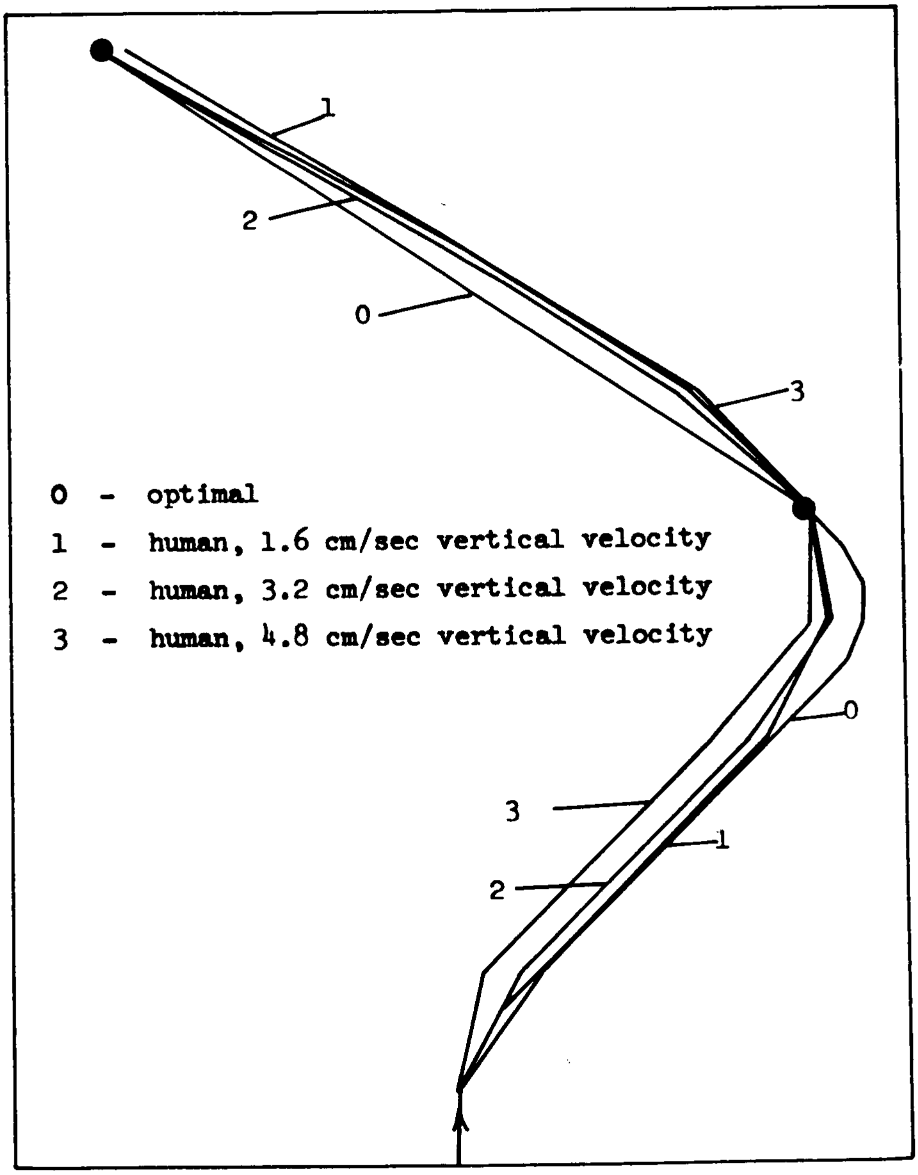

Figure 13b. Human attempt to produce optimal trajectory in two target experiment. More experienced subject. Spot started at bottom and moved with constant velocity to top; each time subject tapped key left or right, velocity changed by one increment in corresponding direction. Trajectories shown are averages of fifteen runs at indicated vertical speed.

increased vertical speed forced the average trajectory in the expected direction of less "planning ahead"; nevertheless the shapes of the human response for all speeds are rather similar and appear consistently different from the optimal.